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LOW ALTITUDE TECHNIQUE FOR MEASUREMENT OF STABILITY FACTORS OF BOMBS

by

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The Low Altitude Technique for the Measurement of the Stability Factors of Bombs

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SUMMARY

For a bomb to be aimable it must be stable. Early in the development stage of new bombs, therefore, stability tests must be carried out. Previous notes[1,2] have dealt with the theory of stability and the motion of a bomb when recovering from disturbances, damped simple harmonic motion having been shown to be a usual component of the motion. This note describes the technique developed at the R.A.E. for studying the behaviour of bombs in disturbed flight and thereby obtaining a quantitative assessment of their stability. The tests are carried out full scale from low altitudes, and from the characteristics of the damped S.H.M. performed by the bomb, stability factors are obtained. These factors are independent of the conditions of test and size of the bomb and can therefore be used directly to compare the stability of different types of bomb.

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1 Introduction

For a bomb to fulfil its function it must be capable of being aimed i.e. the forward throw of all bombs of the same type under given conditions of release must be reasonably constant. One of the most essential properties a bomb must possess to ensure this consistency is stability; the bomb must fly nose into wind, to ensure that all bombs of that type present the same frontage to the resistance of the air and therefore suffer the same drag. Also if disturbed from this attitude by some external force the bomb must recover quickly. If a bomb is unstable it oscillates or cartwheels and its drag will vary so erratically that its performance will be unpredictable.

During the development of a new store it is necessary therefore to test it for stability. A quantitative method of assessing the stability of bombs was developed at this establishment in 1942 and has since been applied to a large variety of bombs, pyrotechnics etc. It is the purpose of this note to describe in detail the technique of these tests including such theory as has not already been dealt with in previous notes.

2 Derivation of the Stability Factors

Analysis of the motion of a bomb during the early stages of its trajectory has shown[1] that the bomb recovers from a small disturbance in pitch by means of a damped simple harmonic motion and from a disturbance in yaw by a damped S.H.M. superimposed on a subsidence. Furthermore the values of the time period, T, and the damping factor, K, of the oscillation have been obtained and their physical significance interpreted in terms of the drag and lift forces[2]. In general a bomb released from an aircraft will receive disturbances in both pitch and yaw, the amplitudes in the two planes not necessarily being the same. The resulting motion can be shown[3] to consist of a damped spin, elliptical in form, which can however be resolved into damped S.H.M. in the two planes, the values of the damping factor and time period for the two components being identical. A study of the oscillations in one plane is therefore sufficient in practical observations on stability.

Considering the motion of a bomb disturbed in pitch, the equation of motion has been shown[1] to be of the form

$$q = \dot{\theta} = Ae^{-Kt} \cos\left(\frac{2\pi t}{T} + \gamma\right)$$

integration of this giving:-

$$\theta = \theta_o e^{-Kt} \cos\left(\frac{2\pi t}{T} + \alpha\right) \qquad \text{..........(1)}$$

where q = angular velocity in pitch

θ = angular displacement of the bomb

K = damping factor

T = time period

A = a constant

γ = a constant

θ_o = initial amplitude of the oscillation

α = phase displacement at zero time

The values of the time period, T, and damping factor K in terms of the stability derivatives are given by

$$T = 2\pi\sqrt{-\frac{B}{UM_W}} \qquad \text{..........(2)}$$

and

$$K = -\tfrac{1}{2}\left(Z_W + \frac{M_Q}{B}\right) \qquad \text{..........(3)}$$

B is the moment of inertia of the bomb about an axis through the centre of gravity and perpendicular to the longitudinal axis.

U is the forward velocity of the bomb along its longitudinal axis.

Z_W, M_Q and M_W are stability derivatives defined as follows.

Z_W is the lateral aerodynamic force due to unit lateral velocity, divided by the mass of the bomb, this force being considered along the direction of the lateral velocity.

M_W is the aerodynamic couple about an axis perpendicular to the longitudinal axis and passing through the centre of gravity, caused by unit lateral velocity along an axis perpendicular to the longitudinal axis and to the axis about which the couple is measured.

M_Q is the aerodynamic couple about an axis perpendicular to the longitudinal axis and passing through the centre of gravity, caused by unit angular velocity of rotation of the bomb about the axis about which the couple is measured.

The values of these derivatives are dependent on the axial velocity U. This velocity is, of course, not constant during the fall of the bomb and neither therefore are the derivatives. Strictly speaking therefore there is no unique value for T and K. In practice the mean values of T and K are obtained over the first few hundred feet of fall and the velocity U is assumed constant and equal to the speed of the aircraft at release.

In order to make direct comparison between bombs of different types tested under different conditions, it has been found convenient to reduce the time period and damping factor as given by equations (2) and (3) to a non dimensional form independent of the scale of the bomb, release speed and air density. To do this it is assumed that for all bomb shapes, the radius of gyration is a constant proportion of the length, i.e.

$$B = k_1 m\ell^2 \qquad \text{..........(4)}$$

where m = mass of the bomb

ℓ = length of the bomb

k_1 = a constant

Substituting this value of B in equation (2) together with the value of the couple M_W as given in Tech. Note Arm.81, equation 72.

viz. $$M_W = -\frac{1}{U}\left(D + \frac{\delta L}{\delta\beta}\right) k_2 \ell$$

we have

$$T = 2\pi\sqrt{\frac{k_1\, m\ell^2}{k_2\, \ell(D + \frac{\delta L}{\delta\beta})}}$$

D and L are the total drag and lift forces on the bomb and $\frac{\delta L}{\delta\beta}$ the lift gradient.

Now

$$D + \frac{\delta L}{\delta\beta} = \tfrac{1}{2}\rho S U^2 \left(C_D + \frac{\delta C_L}{\delta\beta}\right)$$

$$= k_3 \rho S U^2$$

where k_3 is a constant

ρ is the air density

S is the maximum cross sectional area of the bomb.

assuming that the C_L/β curve is a straight line, which it normally is for bombs over small angles of incidence.

$$\therefore \quad T = 2\pi\sqrt{\frac{k_1\, m\ell^2}{k_2 k_3 \rho\, S\ell U^2}}$$

or

$$\frac{UT}{\ell} \cdot \sqrt{\frac{\rho S\ell}{m}} = 2\pi\sqrt{\frac{k_1}{k_2 k_3}} = \text{constant}$$

The ratio $\frac{m}{\rho S\ell}$ will be denoted by μ - which is therefore in effect an approximate measure of the relative density of the bomb to the air in which it is moving.

We have therefore $\frac{UT}{\ell\sqrt{\mu}}$ = constant ....(5)

To make a similar transformation with equation 3, we find by reference to equation 7 of Tech. Note Arm. 81 that

$$Z_W = -\frac{1}{mU}\left(D + \frac{\delta L}{\delta\beta}\right)$$

and

$$M_Q = -\frac{1}{U}\left(D + \frac{\delta L}{\delta\beta}\right) k_4 \ell^2 \qquad k_4 \text{ is a constant.}$$

Substituting these values in equation (3) and using the value of B as given in equation (4) then,

$$K = \frac{1}{2}\left\{\frac{D + \frac{\delta L}{\delta \beta}}{mU} + \frac{k_4 \ell^2 \left(D + \frac{\delta L}{\delta \beta}\right)}{U\, k_1\, m\ell^2}\right\}$$

$$= \frac{D + \frac{\delta L}{\delta \beta}}{2mU}\left(1 + \frac{k_4}{k_1}\right)$$

As before

$$\left(D + \frac{\delta L}{\delta \beta}\right) = k_3 \rho S U^2$$

$$\therefore K = \frac{k_3 \rho S U}{2m}\left(1 + \frac{k_4}{k_1}\right)$$

$$\frac{Km}{U\rho S} = \frac{k_3}{2}\left(1 + \frac{k_4}{k_1}\right)$$

or

$$\frac{K\mu\ell}{U} = \text{constant} \quad \ldots\ldots\ldots\ldots (6)$$

The expressions $\frac{UT}{\ell\sqrt{\mu}}$ and $\frac{K\mu\ell}{U}$ are known as the stability factors of the bomb.

In the early days of this work (1942), T and K were quoted in reports, together with the time required to halve the amplitude of the oscillation. Later, allowance for scale was introduced and the factors became $\frac{T}{\ell} \times 10^2$ and $K\ell$, the speed of release being kept constant at 180 m.p.h. in all trials. Occasionally trials were carried out at speeds other than 180 m.p.h. in which case a correction was applied. Finally, in April 1944, U was incorporated in the factors which then became $\frac{UT}{\ell} \times 10^{-1}$ and $\frac{K\ell}{U} \times 10^3$, - the multiples of 10 being introduced to reduce the factors to a convenient magnitude. The factors in this form were in use up to May 1946 and used thus in all reports. It has recently been decided, however, to introduce μ, thereby making the factors more universal in their application by the introduction of mass and air density effects. Under present conditions of trials - viz: altitudes less than 1500 ft. - air density effects will be due only to seasonal changes and not to height. Variations in air density due to seasonal changes in temperature and pressure can be shown to have only a small effect on the value of μ. The values of the new stability factors have, therefore, been calculated for all stores tested since the inception of stability trials assuming the air density, ρ, to be constant at a standard value of 4.42×10^{-5} lb./ins.^{3}. All these results have been classified and published in a technical note[14].

3 The Technique of Stability Trials

3.0 Introduction

Briefly, a stability trial consists of the release of the bomb under test from an aircraft flying at a known airspeed at a height of between 300 and 1500 ft. depending on the size of the store (see para. 3.1). A pitching oscillation is imparted to the store at release (para.3.2) and its subsequent flight is photographed from the ground by a high speed cine camera (para.3.3). The film thus obtained is analysed (para.4) by measuring the angle between the bomb axis and some arbitrary datum and plotting these angles against time as given by a time base on the film. From the graph, values for the time period and damping factor are calculated and converted into the stability factors.

3.1 Layout of the Bombing Range (Fig.1)

A diagrammatic sketch of the range layout during a stability trial is shown in Fig.1. The site for the camera requires careful consideration for the following reasons.

(i) A clear view of the target area and along the line of flight of the bombing aircraft is required.

(ii) The line from camera to target should point in a northerly direction so that the sun is approximately behind the camera.

(iii) A clear image of the bomb is essential on the film, large enough to define the axis of the bomb with reasonable accuracy.

(iv) Errors due to panning of the camera, i.e. the angularity effect due to the movement of the bomb relative to the camera, must be minimised.

Requirements (iii) and (iv) are contradictory, the former implying a short distance between camera and store and the latter as great a distance as possible to reduce the angular movement of the camera. Height of release requires to be low on both these counts, but must be sufficient to allow several oscillations to be completed by the bomb before impact.

In practice, two camera positions are in general use, the choice depending on the size of the store viz:

(a) the distance, D, (Fig.1) of the camera from the target is about 500 yds. for stores greater than about 30 inches in length, the height of release in such cases being usually 1000 ft. or slightly less. Occasionally a height of 1500 ft. has been used in the case of large stores (1000 lb.) to ensure sufficient oscillation for analysis.

(b) the distance D is about 150 to 200 yds. for small stores such as pyrotechnics, incendiary bombs etc., the height of release then being between 300 and 600 ft.

It can be shown from the geometry of the layout that under these conditions the effect of distortion on the damping factor, due to panning is quite small; time period measurements are of course not affected.

Radio communication between aircraft and ground is maintained during the trial, to give the camera operator warning of the instant of release.

3.2 Methods of Oscillating the Bomb

3.21 Natural Disturbances

The earliest method of causing bombs to oscillate was a very simple and convenient one merely using the natural disturbance given to bombs released from the wing carriers of certain aircraft. The Hampden aircraft, which was the first to be used on this work, was found to give an amplitude of oscillation of about 20°.-.30° to a store released from its wing carriers at about 180 m.p.h. if the store were crutched nose up on the carrier. Typhoon and Tempest aircraft have since been used occasionally in the same manner, but usually at higher speeds, in particular when the bomb under test was intended for fighter-bomber use. This method has the disadvantage of restricting the number of bombs to two per flight and this, together with the introduction to a Lancaster for bombing trials, led to other methods being devised.

A convenient method of oscillating small stores is by releasing them from the standard flare launching chute. If launched tail first, the store enters the airstream at an angle of approximately 70° to the horizontal, or if launched nose first, the angle is about 110°. These are severe conditions of release and are normally only used for stores which are designed either for chute launching e.g. pyrotechnics, flares, etc. or for release from clusters e.g. incendiary, fragmentation bombs etc.

With very small stores up to about 10 lb., hand launching through an aperture in the floor of the aircraft may be used; any required initial angle of disturbance may then be chosen. This method has been used with 4 lb. and 2 lb. incendiary bombs.

3.22 Arming Wire and Safety Clip Method

To impart a pitching oscillation to a bomb, a force must be applied to either nose or tail. In order to keep this force reasonably small, thereby preventing damage to the aircraft and bomb, it must be made to act for a reasonable length of time, i.e. over some distance of fall of the bomb. A breaking cord, for example, attached to the aircraft and the bomb tail (or nose) applies an impulsive force which, therefore, requires to be large. It was found that the safety clip (Fahnestock) used in horizontal fuzing systems on bombs gave a reasonably constant frictional load when sliding along the phosphor-bronze arming wire. This load could be varied by using an appropriate number of clips on the wire. To apply this force to the tail of a bomb a small hole (about 1/8" dia.) was drilled in the top of the tail drum (i.e. in line with the lug) or other suitable position. Through this hole was placed a phosphor-bronze arming wire, loop end uppermost. Safety clips were slid onto the lower end of the wire and pushed hard up against the inside of the tail drum. The number of clips used depended on the weight of the bomb and was determined experimentally. Approximately 10 to 12 clips were required to give a 500 lb. bomb a disturbance of about 20°. When the bomb was loaded into the aircraft the loop of the arming wire was secured to the aircraft structure immediately above by means of a strong cord. As the bomb commenced to fall, therefore, the tail drum slid down the arming wire taking the clips with it; the retardation of the tail due to the force required to move the clips down the wire, imparts a nose down pitch to the bomb. Many failures occurred, however, due it is believed to clips breaking and the scheme was found to be quite inadequate for use with 1000 lb. stores. It was, therefore, abandoned in favour of the following scheme.

3.23 Clip and Wire Method (Fig. 2)

Developed in the first instance for use on 1000 lb. stores, this device is now used on all carrier-released stores. In principle it is the same as the method described in the previous paragraph, but is more robust and capable of applying a greater force. Instead of Fahnestock clips, a special clip is made consisting of two steel plates 1" × $\frac{1}{2}$" × $\frac{1}{8}$" (A, Fig. 2). The two plates are bolted together to grip the wire. Piano or high tensile steel wire of 10-14 S.W.G. is used having a loop (B) formed at one end. The clip is fixed on the wire as near to the loop as possible in the first place. The bolts are then adjusted until the load required to cause the clip to slide steadily along the wire is some predetermined value, measured by means of a spring balance. The wire is then cut to the required length from clip to free end.

Attachment to the bomb can be made in a similar manner to that described in the previous paragraph i.e. through a hole inthe tail drum, the tail drum being of course between the clip and the loop. In practice, however, large loads may be experienced and the use of the tail drum is to be avoided if possible to prevent distortion. Where possible, therefore, an eyebolt (C) is threaded on the wire between loop and clip, before the latter is adjusted. The eyebolt carrying the wire can then be screwed into a previously prepared hole in the bomb immediately before the trial. Fig. 2a shows such an arrangement on a cluster bomb in a Lancaster bomb bay.

There are obviously two possible variables, the force required to move the clip and the length of wire. When fixing these two quantities the following practical points must be considered.

(a) The force must not be so great as to damage the attachment points on either the aircraft or the bomb.

(b) Too great a force may cause binding between clip and wire.

(c) The length of wire should be kept to a minimum to prevent fouling on control wires etc.

For a given bomb the amplitude of oscillation obtained is roughly proportional to the force and to the square root of the distance over which it acts. It has been found by experience that about four feet is the maximum safe length and 100 lb. the maximum safe force which can be used. A force of 50 lb. acting over three feet of wire is a typical combination used on a 500 lb. bomb, whereas a 1000 lb. bomb requires about 100 lb. over four feet.

This scheme has proved reliable if sufficient care is taken in preparation and it is reasonably simple to make. It is not reliable, however, from the point of view of consistency in operation, a number of wires all nominally of the same length and loading when applied to a number of bombs of the same type may give widely different disturbances to these bombs. This is generally of no great importance since, so long as an oscillation is set up, analysis is usually possible and, if too great a disturbance is given, the preliminary oscillations are neglected (see para.4.3). In certain cases, however, where stores tend to whirl under conditions of severe disturbance it is of interest to know the critical angle beyond which whirling will occur (see para.4.52).

3.24 Hinged Flaps

A method was devised but only used once, whereby aerodynamic forces were used to initiate an oscillation. A deflector plate was fitted behind the tail drum at an angle of about 45° to the airflow through the drum to provide a lift force. The plate could be designed to give disturbances in either pitch or yaw. The plate was so arranged that after about 12 feet of fall it became detached from the bomb.

In the case of yawing oscillations, it was intended to photograph the flight of the bomb by a camera mounted in the bomb bay viewing downwards. Stability experiments could then be carried out at any altitude independent of ground cameras and could be combined with functioning and other trials.

The disadvantages of these schemes were:-

(a) they were only applicable to cone and drum type tails.

(b) the dimensions of the plate depended on those of the tail drum and therefore special plates had to be made for each type of store.

(c) the plate was expendable.

(d) slots and holes were required in the tail drum.

(e) a long static line has to be stowed and if possible retracted to prevent fouling on aircraft structure and other stores.

For these reasons the scheme was abandoned early in its experimental stage.

3.25 Braked Winch

A scheme has been designed, but as yet not tried, whereby it is hoped consistent and predetermined initial angles of disturbance can be obtained. The scheme consists of a grooved drum on which is wound seven feet of cable. The free end of the cable is to be attached to some suitable point on the bomb and is pulled out as the bomb falls. The rotation of the drum is controlled through gears by a centrifugal brake consisting of four weighted brake shoes sliding on radial arms. The brake shoes bear on the inside of a fixed brake drum and the amount of braking can be adjusted by means of springs acting on the brake shoes.

The cable will be released from the bomb and retracted by means of a clock spring inside the cable drum. The release of the cable from the bomb is designed to occur when the bomb has reached a certain angle of pitch.

At the time of writing, the prototype winch is being manufactured and all laboratory tests and flight trials are still to be done. No comments can be made therefore on the efficiency of the device.

3.3 The Camera

Three types of camera have been used for photographing the fall of the bomb, the Vinten high speed cine camera, the Newman Sinclair cine camera and the Strip camera. The first two are standard 35 mm. moving picture cameras while the latter works on an entirely different principle.

3.31 The Vinten Camera

This is an electrically driven high speed camera normally fitted with a lens of 12 inches focal length when used under the conditions described in para.3.1. A time base on the film is provided by means of an induction coil supplying a spark gap inside the camera and controlled by an electrically driven 50 cycle tuning fork. The spark is recorded on the edge of the film. A camera speed of approximately 50 frames per sec. is the most convenient for stability work, though the actual speed obtained in practice varies from about 30 to 70 frames per sec.

Fig.3 shows sample frames (not consecutive) taken from a Vinten film, the first (Fig.3a) illustrating the motion of a stable bomb executing damped simple harmonic motion and the second (Fig.3b) an unstable bomb cartwheeling.

3.32 The Newman Sinclair Camera

This is a clockwork driven camera capable of speeds up to 24 frames per sec. A lens of 12" focal length is again used. A time base has been specially fitted to this type of camera for work such as stability trials requiring a knowledge of the frame speed.

This camera has been used in the past when Vinten cameras were not always available due to pressure of other work.

3.33 The Strip Camera

As pointed out in para.3.1 the use of a cine camera does involve errors due to rotation of the camera. To avoid these errors a strip camera was obtained in 1942. This is a plate camera, taking a plate $22\frac{1}{2}$ inches long by $6\frac{3}{4}$ inches high and fitted with a 15 inch lens. Briefly, the mechanism consists of an electro-magnetically operated louvre shutter behind the lens, together with a slit moving in a mask across the focal plane. The movement of this slit across the plate is controlled by the operator using a handwheel, while following the bomb through a suitable sight, the arrangement being such that the louvre shutter operates each time the slit has moved its own width. The camera thus produces a succession of vertical strip pictures on the plate, the whole picture forming a panoramic view of the trajectory. To eliminate blur, the lens is rotated one revolution in a circle of circumference 0.2 inch while the slit is moving its own width. The shutter is phased to open just before the lens reaches the top of its travel and closes just after passing this point. The plate accommodates 101 pictures each 0.2 inch wide taken at a maximum speed of about 12 strips per second, the exposure time being 1/70 second. The time interval between successive exposures is given by means of a chronograph consisting of a paper strip driven by a gramophone motor. Two magnetically operated pencils bear on the paper, one giving half second beats from a clock and the other recording each opening of the shutter.

The camera had several disadvantages and certain limitations and it was eventually discarded. The main objection was that a height limitation of 500 feet had to be imposed at the bombing range then in use, the maximum available distance between camera and target being about 2,600 ft. A distance of 4,700 ft. would have been required to photograph a store released at 1000 feet and the image on the film would then be too minute for analysis.

A detailed description of the camera is given in the specification No.ARL/R6/H24 prepared by the Admiralty Research Laboratory.

4 Analysis of Results

4.1 Theory of Damped Simple Harmonic Motion

The equation of damped S.H.M. is of the form

$$\theta = \theta_o e^{-Kt} \cos \left(\frac{2\pi t}{T} + \alpha\right)$$

the symbols having been defined in para. 2. Such a curve is illustrated for comparison purposes in Fig.5a, its most important feature being that the ratio of successive maximum oscillations is constant.

If we consider two successive maxima θ_1 and θ_2 occurring at times t and t + T/2 respectively, then

$$\theta_1 = \theta_o e^{-Kt} \cos \left(\frac{2\pi t}{T} + \alpha\right)$$

and

$$\theta_2 = \theta_o e^{-K(t + \frac{T}{2})} \cos \left\{\frac{2\pi}{T}\left(t + \frac{T}{2}\right) + \alpha\right\}$$

Dividing, we get

$$\frac{\theta_1}{\theta_2} = - e^{\frac{KT}{2}}$$

$$\therefore \frac{KT}{2} = \log_e \left|\frac{\theta_1}{\theta_2}\right| \text{ numerically}$$

$$K = \frac{2}{T} \log_e \left|\frac{\theta_1}{\theta_2}\right| \qquad \text{.............(7)}$$

The method of obtaining the curve of an oscillating bomb and the application of the above formula is dealt with in the following paragraph.

4.2 Film Reading

The film negative (of which Fig.3 shows selected prints) is put through a step by step projector which throws the picture downwards on to a white circular disc, pivoted at its centre and ruled across with a grid of parallel lines. The disc is graduated in degrees around its circumference, this scale being read against a pointer fixed to the table. Frames are taken at regular intervals - usually every fourth or fifth if the speed is about 50 frames per second, but depending of course on the time period of the oscillation - and the angle of the bomb image measured by rotating the disc until the grid lines are parallel to the bomb axis. The zero position of the disc is fixed but quite arbitrary. A graph is then drawn, the angles being plotted as ordinates and the number of frames as abscissa (see Fig.4). The film speed is obtained in frames per second by reference to the 50 cycle time base on the edge of the film.

Fig.4 is a typical curve obtained for a stable bomb; the method used to analyse this curve is dealt with in the following para., the full analysis being given in the Figure. Variations of this type of curve are described in para.4.4 and other types of motion in para.4.5.

4.3 Analysis of the Curve (Fig.4)

All oscillation curves obtained for bombs in stability trials differ from normal damped S.H.M. curves (cf. Fig.5a) in so far as they are not symmetrical about the time axis due to curvature of the trajectory about which the bomb is oscillating. It is possible to make an allowance for this by replotting the curve as follows. The envelopes to the curve are drawn, AL and A'L', both upper and lower portions of which should be smooth curves touching each peak. The centre line between the two envelopes is then drawn by taking the mid points a, b, c etc. of ordinates drawn between the two envelopes. This centre line should also be a smooth curve. The oscillation curve is then replotted as shown in Fig.5b by converting the centre line, al, into the horizontal time axis, ck, of Fig.5b. The ordinates of points on the original curve are measured from the centre line, al,(Fig.4) and replotted as ordinates from the axis, ck, in Fig.5b. It has been found in practice that replotting does not greatly affect the results (T is of course unaffected) and during the war was not considered worth the extra work involved.

To analyse the original curve direct, therefore, the envelopes are drawn as described above but the centre line is not necessary. Ordinates AA', BB' .... LL' are dropped from each peak to the opposite envelope. By a convention arrived at through experience, all such ordinates whose overall length represents an angle greater than 70° (e.g. AA' and BB') or less than 10° (e.g. LL') are neglected.

The time period, T , is obtained from

$$T = \frac{\text{MN frames}}{3.5 \times (\text{film speed})} \text{ secs.}$$

Theoretically (para.4.1) the ratios $\frac{CC'}{DD'}$, $\frac{DD'}{EE'}$ .... $\frac{JJ'}{KK'}$ should be equal and at equal time intervals, T/2. In practice, however, they vary and to obtain K each ratio is substituted in equation (7) for $\frac{\theta_1}{\theta_2}$ together with the appropriate time interval.

Thus the first value for K is obtained from

$$K = \frac{2}{\tau} \log \frac{CC'}{DD'}$$

where τ is the time from C to D'.

In this way seven values of K are obtained. To maintain equal weighting of the values of θ used, a further value of K is obtained by taking the ratio CC'/KK' and the appropriate value of T viz: the time from C to K'.

The analysis is shown in tabulated form on Fig.4.

A mean of eight values then gives K.

The replotted curve, Fig.5b, is analysed in the same way except that envelopes are unnecessary, the ratios used being Cc/D'd, D'd/Ee

.... Jj/K'k.

The values of T and K thus obtained are converted into the stability factors $UT/\ell\sqrt{\mu}$ and $K\mu\ell/U$ by a knowledge of the indicated airspeed of the aircraft at release, the air density, ρ, and the dimensions of the store (mass, m, length, ℓ, diameter, d). Usually about four or six bombs of any one type are tested, the mean values of the stability factors and the probable error of an individual result being quoted. The probable error is given by

$$P.E. = 0.674 \sqrt{\frac{\sum_{1}^{n} (x_n - \bar{x})^2}{n - 1}}$$

where n is the number of results

x_n an individual value of a stability factor

$\bar{x}$ the mean value.

Owing to the small number of results obtained in the past on any one type, the probable error has no great significance beyond giving a guide to the extent of the scatter of the results.

4.4 Irregular Curves (Fig. 6)

It is frequently found that smooth envelopes cannot be drawn to touch all the peaks of a curve. This may be due to one or more of several effects, viz:-

(a) errors in reading angles from the film
(b) obliquity of the camera
(c) borderline stability
(d) aerodynamic forces caused by air pockets, variations in air density etc. particularly affecting small stores.

If the irregularity in the curve is small, it is usually easy to fit by eye the best smooth envelope. Analysis then proceeds as described in para. 4.3, ordinates always being drawn between the envelopes in cases where the envelope cuts, or does not touch, the curve.

If the irregularity of the peak points makes the fitting of a smooth curve difficult as in Fig. 6, a slightly different method is used. The envelopes BH and AJ are drawn to touch each peak. Centre points of ordinates drawn between the two envelopes at regular intervals are plotted and a smoothed centre line, aj, fitted by eye, through these points. Ordinates are now drawn from each peak to the smooth centre line, Aa, Bb .... Jj. Any such ordinate which exceeds 35^o or is less than 5^o is neglected as before.

The time period is given by

$$T = \frac{\text{MN frames}}{4 \times (\text{film speed})} \text{ secs.}$$

The ratios Aa/Bb, Bb/Cc, ... Hh/Jj and Aa/Jj are substituted for $\frac{\theta_1}{\theta_2}$ in the formula $K = \frac{2}{\tau} \log \frac{\theta_1}{\theta_2}$, τ again being the appropriate time interval between θ_1 and θ_2.

The analysis is tabulated in detail on Fig.6, nine values of the damping factor K being obtained in this particular case. The stability factors, their mean values and probable errors are calculated as before.

4.5 Other Types of Motion

There are two other main types of motion met with in stability work which are of interest. They are the motions attributed to (i) unstable bombs (ii) whirling bombs.

4.51 The motion of an unstable bomb usually takes the form of an increasing oscillation developing, if height is sufficient,into a cartwheel or irregular tumbling. If the initial disturbance is very severe it may in fact cartwheel immediately after release. Such motion is, of course, not analysable and curves are in fact, seldom drawn, the motion being obvious from visual observation of the drops or directly from the film.

4.52 The theory of whirling and its occurrence in practice has been dealt with in References 5 and 4 respectively. The oscillation curve of a whirling bomb (Fig.7) is usually drawn to ensure that the motion is not merely a case of very poor damping, and also because the following information is of general interest.

(a) the time period, usually found to be significantly smaller than that for identical bombs which executed damped S.H.M.

(b) the order of the initial amplitude at release.

(c) the amplitude of the whirl.

It is hoped that in the future a greater degree of control over the initial disturbance given to carrier released stores will be possible by means of the apparatus described in para.3.35. If this is achieved, it should be possible to carry out a series of drops, without causing any of the stores to whirl or alternatively to find the greatest angle of disturbance allowable without causing whirling.

5 Criterion Values

About 170 different types of stores ranging from 2 lb. to 1000 lb. have been tested at R.A.E. by the method described in this note and about 26 of these have undergone trials to measure their ballistic dispersion by a stick bombing technique[6] developed at the R.A.E. All results from these two types of test have been collected and classified in a Tech. Note[4], which also quotes some results obtained in ballistic trials at Orfordness Research Station by a single dropping technique[7].

From these trial results criterion values for the stability factors have been derived. They are as follows:-

$\frac{UT}{\ell\sqrt{\mu}}$ should be less than 2.5

$\frac{K\mu\ell}{U}$ should be greater than 6.0

for a store to have a ballistic dispersion of less than about 7 mils (probable error in trail distance) - one mil being an error of one foot per thousand feet of release height.

The derivation and application of these criteria is described in Reference 4, to which reference should be made before using them.

6 Limitations of the Technique

6.1 Although stability is an essential property for a bomb to possess in order that it may be aimable, it is not sufficient, ballistic dispersion depending on other factors such as manufacturing variations, asymmetry, high speed effects. Thus stability measurements at low altitudes as described in this note may be used to compare the effects of small variations in design, or to choose the best of several designs, but they must invariably be followed by trials from operational heights. Such trials serve to (a) check the stability of the bomb from high altitudes (i.e. at high Mach numbers), (b) measure the ballistic dispersion.

6.2 It has been found, by experience with bundled type clusters, that misleading and contradictory results may be obtained if the bombs are not symmetrical or not rigid.

6.3 Certain types of bombs e.g. those having plain cylindrical tails which have a small angle of stall, require careful handling in stability trials since the disturbance normally given (about $\pm 30^\circ - 40^\circ$) would immediately cause such a bomb to whirl.

List of Symbols

B	moment of inertia of a bomb about an axis through the centre of gravity and perpendicular to the longitudinal axis
C_D	drag coefficient
C_L	lift coefficient
D	total drag force on bomb
d	maximum diameter of bomb
K	damping factor of a damped simple harmonic motion
L	total lift force on bomb
ℓ	overall length of bomb
M_Q	aerodynamic couple about an axis perpendicular to the longitudinal axis and passing through the centre of gravity, caused by unit angular velocity of rotation of the bomb about the axis about which the couple is measured.
M_W	aerodynamic couple about an axis perpendicular to the longitudinal axis and passing through the centre of gravity, caused by unit lateral velocity along an axis perpendicular to the longitudinal axis and to the axis about which the couple is measured.
m	mass of bomb
n	number of bombs
P.E.	probable error of an individual observation
q	angular velocity in pitch
S	maximum cross sectional area of bomb
T	time period of oscillation
t	time measured from some zero
U	forward velocity of the bomb along its longitudinal axis; the true airspeed of the aircraft
x_n	an individual value of a stability factor
$\bar{x}$	mean value of x_n
Z_W	lateral aerodynamic force due to unit lateral velocity, divided by the mass of the bomb, this force being considered along the direction of the lateral velocity.
α	phase displacement of an oscillation at zero time
β	angle between the longitudinal axis of the bomb and the relative wind
θ	angular displacement of bomb from some arbitrary zero

θ_o	Initial amplitude of oscillation - value of θ at zero time
μ	"relative density" factor = $\frac{m}{\rho S^{\ell}}$
ρ	air density
τ	a time interval

A, Υ, k_1, k_2, k_3, k_4 are constants.

References

No.	Author	Title, etc.
1	J.F. Capper	Note No.1 on the Theory of Bomb Stability. Technical Note Arm.61. June 1942.
2	J.F. Capper	Note No.2 on the Theory of Bomb Stability. Technical Note Arm.81. October 1942.
3	J.F. Capper	Note No.3 on the Theory of Bomb Stability. Technical Note Arm.167. March 1943.
4	Bomb Ballistics Group	The Stability and Consistency of Various Bombs. Technical Note Arm.331. June, 1946.
5	J.F. Capper	Note No.4 on the Theory of Bomb Stability. Technical Note Arm.334. October, 1945.
6	Bomb Ballistics Group, Arm. Dept.	The Stick Bombing Technique for Measuring the Ballistic Dispersion of Bombs. Technical Note Arm.342. July, 1946.
7	-	Bomb Ballistic Experiments at Orfordness. B.T.35. June 1943.

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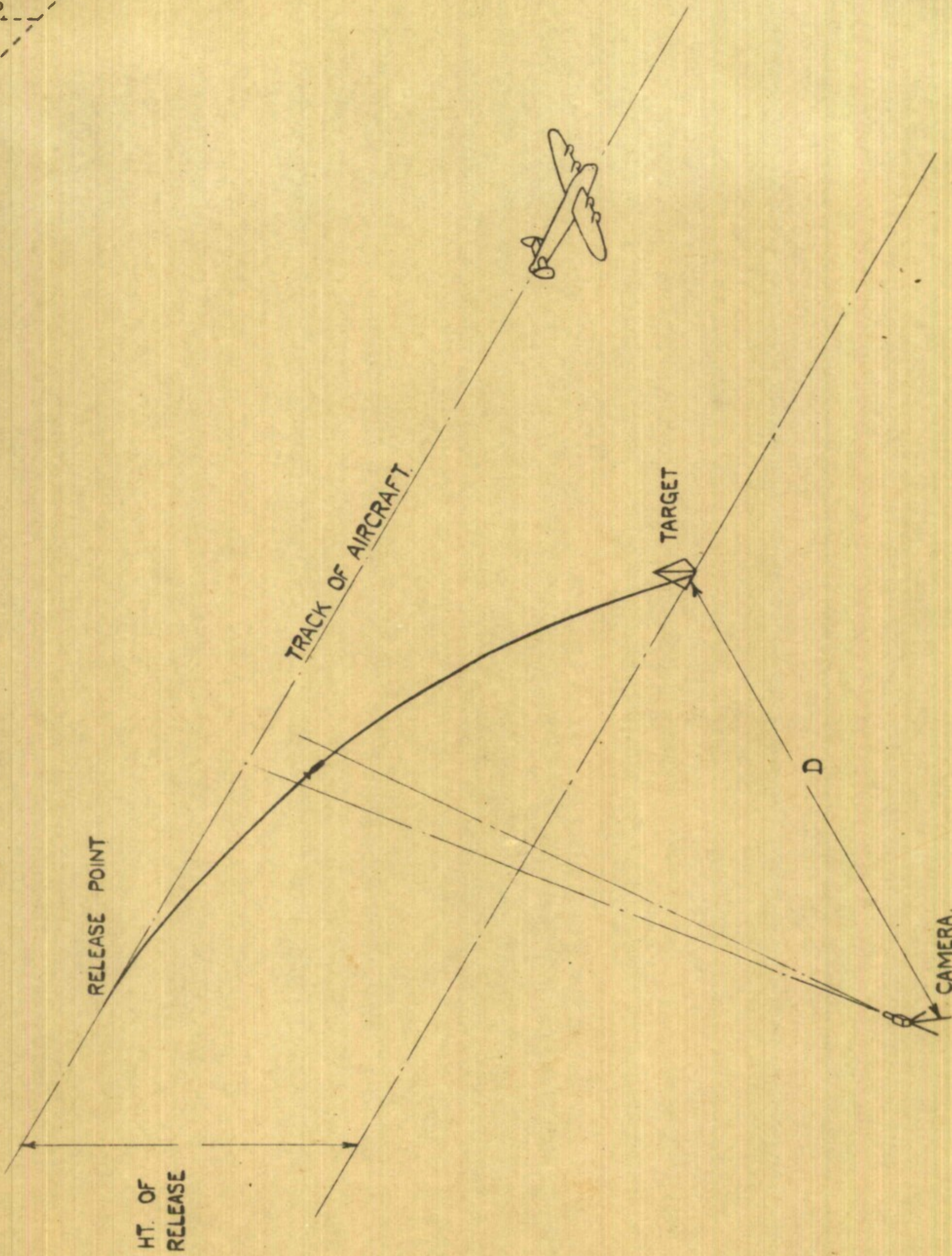
FIG. 1.



LAYOUT OF THE BOMBING RANGE.

FIG'S 2.a & b.

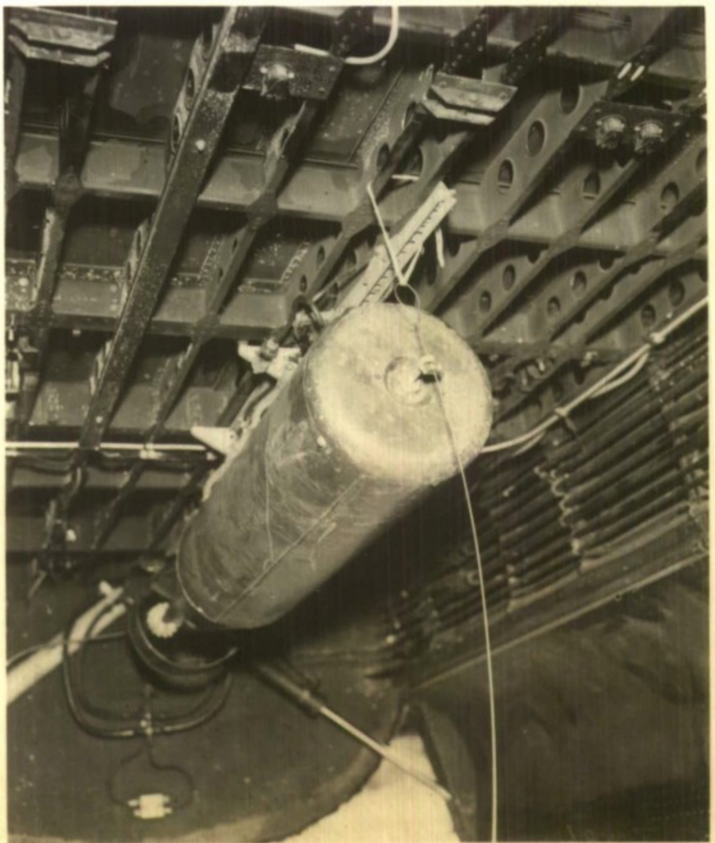


FIG. 2a. OSCILLATING DEVICE FITTED TO CLUSTER.

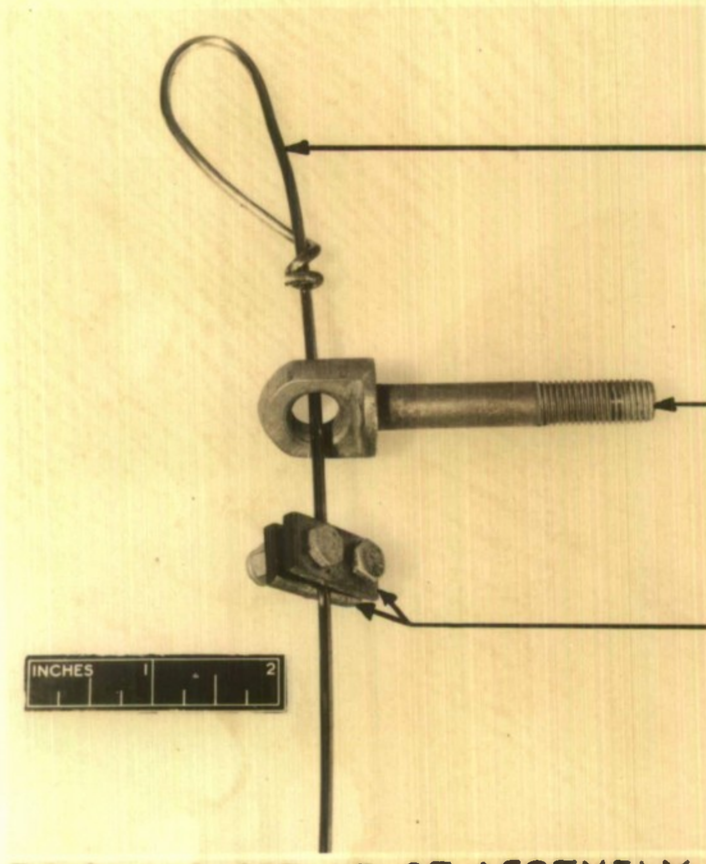
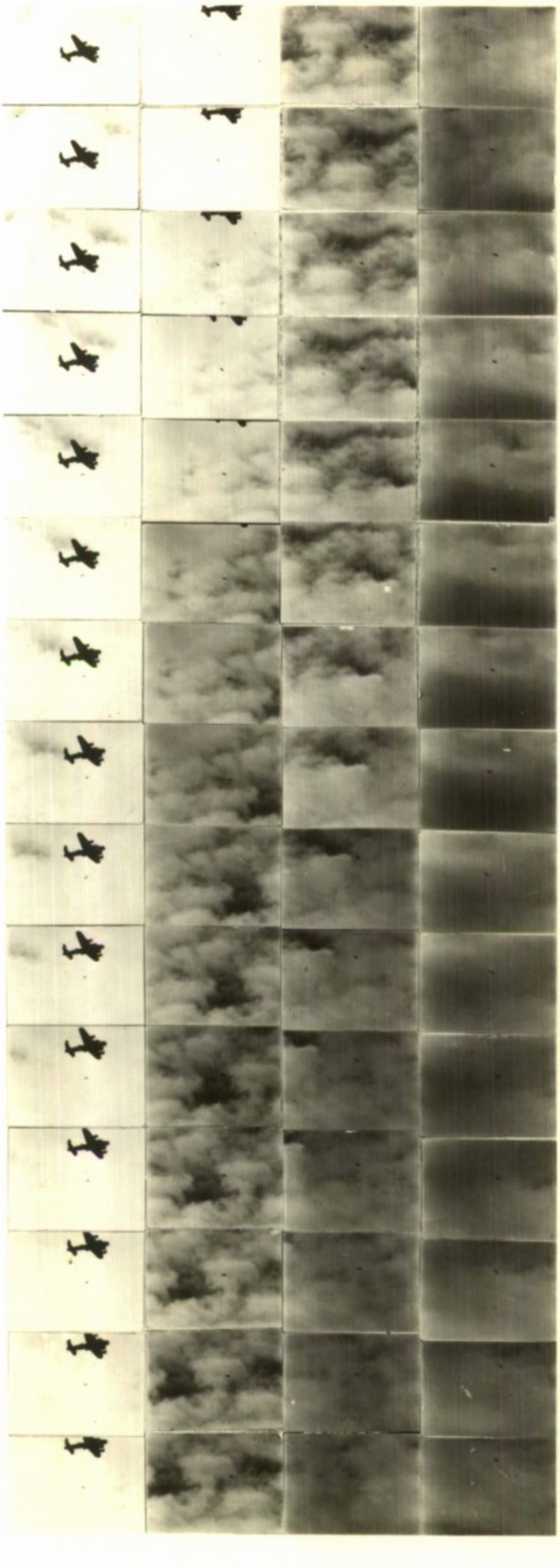


FIG. 2b. CLOSE UP OF ASSEMBLY.

CLIP AND WIRE METHOD OF OSCILLATING BOMBS.

R.A.E. NEG. NO. 70583 /46

FIG. 3



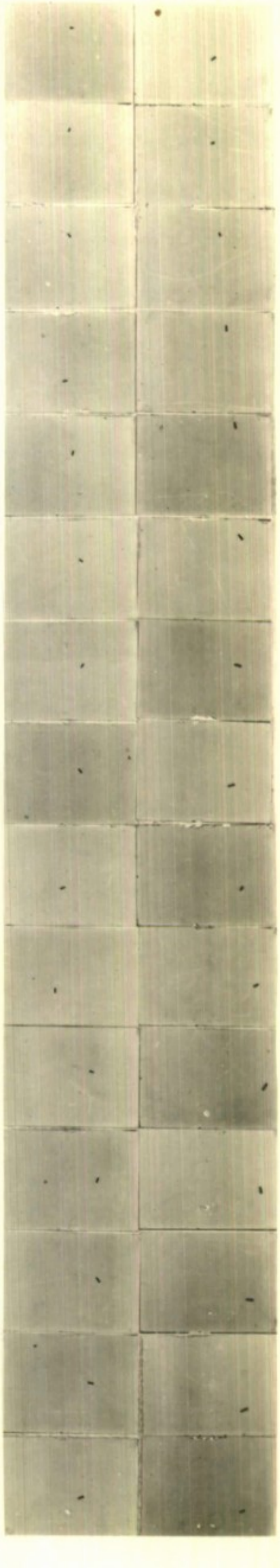


FIG. 3a. SAMPLE FRAMES FROM VINTEN FILM SHOWING BOMB EXECUTING DAMPED S.H.M.
CLIP & WIRE METHOD OF OSCILLATING.
RELEASE AT 1000 FT. AT 180 M.P.H

FIG. 3b. UNSTABLE BOMB CARTWHEELING RELEASE FROM TYPHOON AT 350 M.P.H.

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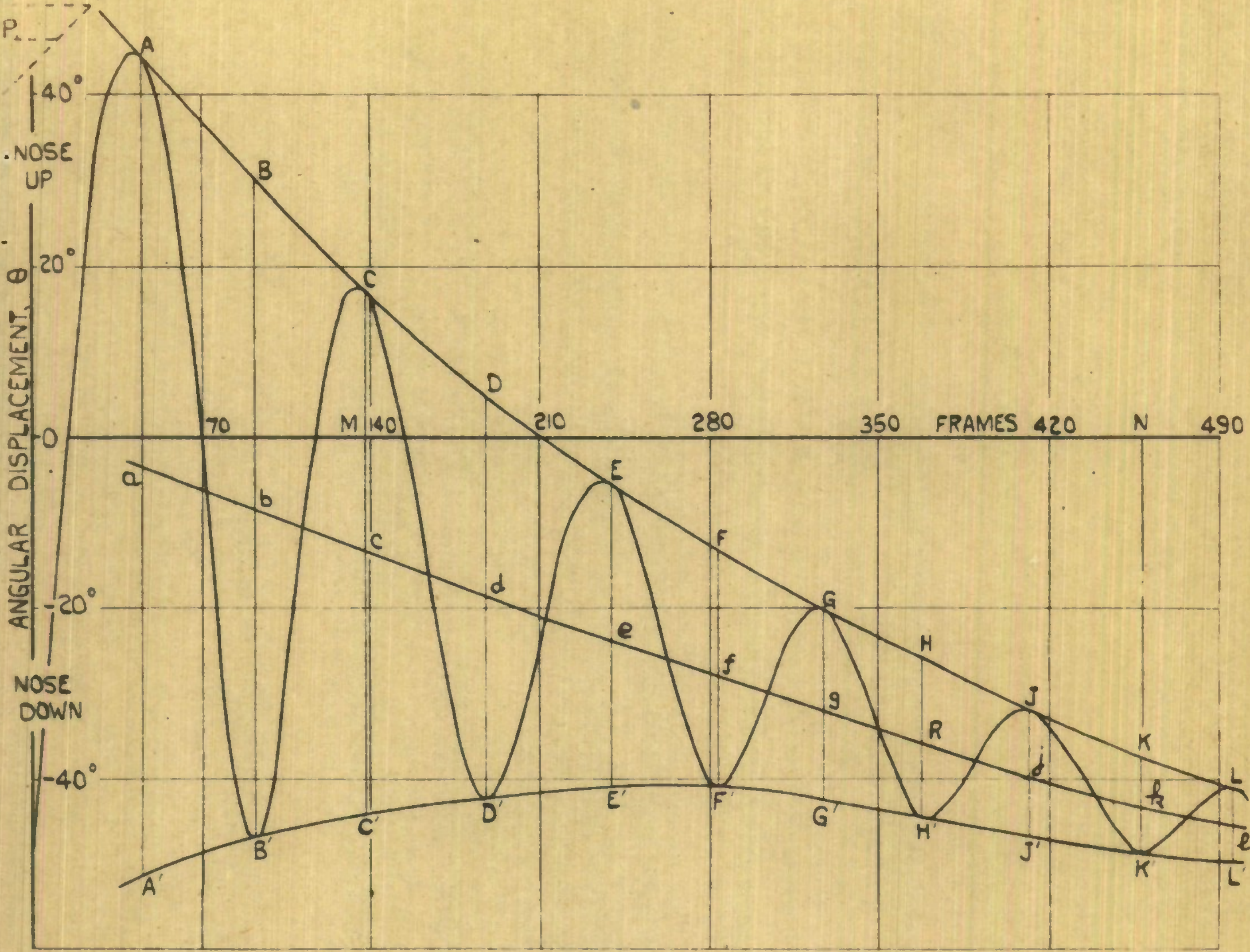
23 9 46

FIG. 4.



FILM SPEED = 73·3 FRAMES/SEC
RELEASE SPEED, U = 180 M.P.H.
LENGTH OF STORE, ℓ = 54 INS.
μ = 1408

$\theta_1 --- \theta_7,\ \theta_1$	61·2	46·8	35·2	27·4	22·0	18·0	14·2	61·2
$\theta_2 ---- \theta_8,\ \theta_8$	46·8	35·2	27·4	22·0	18·0	14·2	10·8	10·8
θ_1/θ_2	1·306	1·328	1·284	1·245	1·222	1·266	1·314	5·667
LOG θ_1/θ_2	0·267	0·284	0·250	0·220	0·201	0·236	0·273	1·735
τ FRAMES	48	52	45	44	40	44	46	319
τ SECS	0·665	0·709	0·614	0·601	0·546	0·601	0·628	4·355
K	0·407	0·399	0·407	0·365	0·366	0·392	0·434	0·398

MEAN $K = 0{\cdot}396\ \text{SEC}^{-1}$

$$T = \frac{MN}{3{\cdot}5 \times 73{\cdot}3} = 1{\cdot}24\ \text{SEC.}$$

$$\frac{UT}{\ell\sqrt{\mu}} = 1{\cdot}94$$

$$\frac{K\mu\ell}{U} = 9{\cdot}50$$

TYPICAL BOMB OSCILLATION CURVE & ANALYSIS.

FIG. 5.

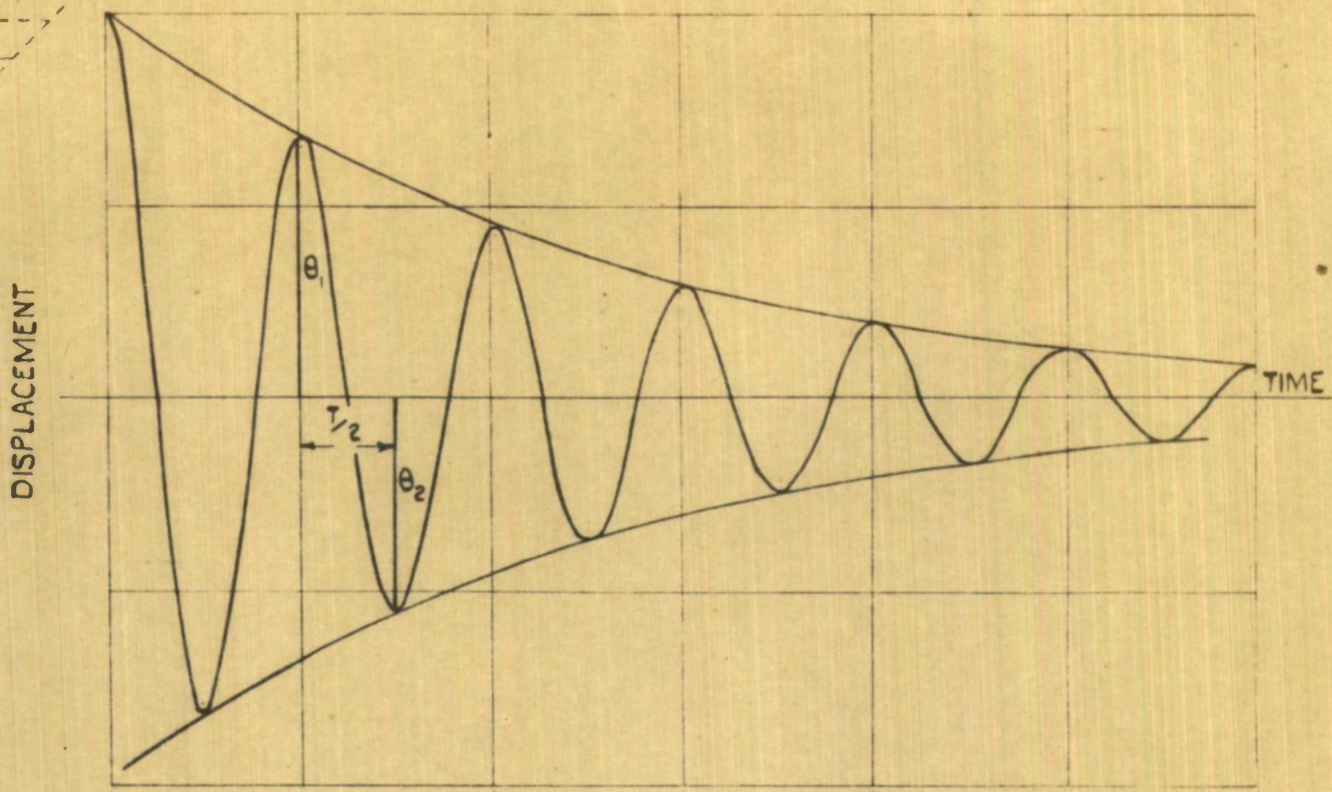


FIG. 5a. DAMPED SIMPLE HARMONIC MOTION.

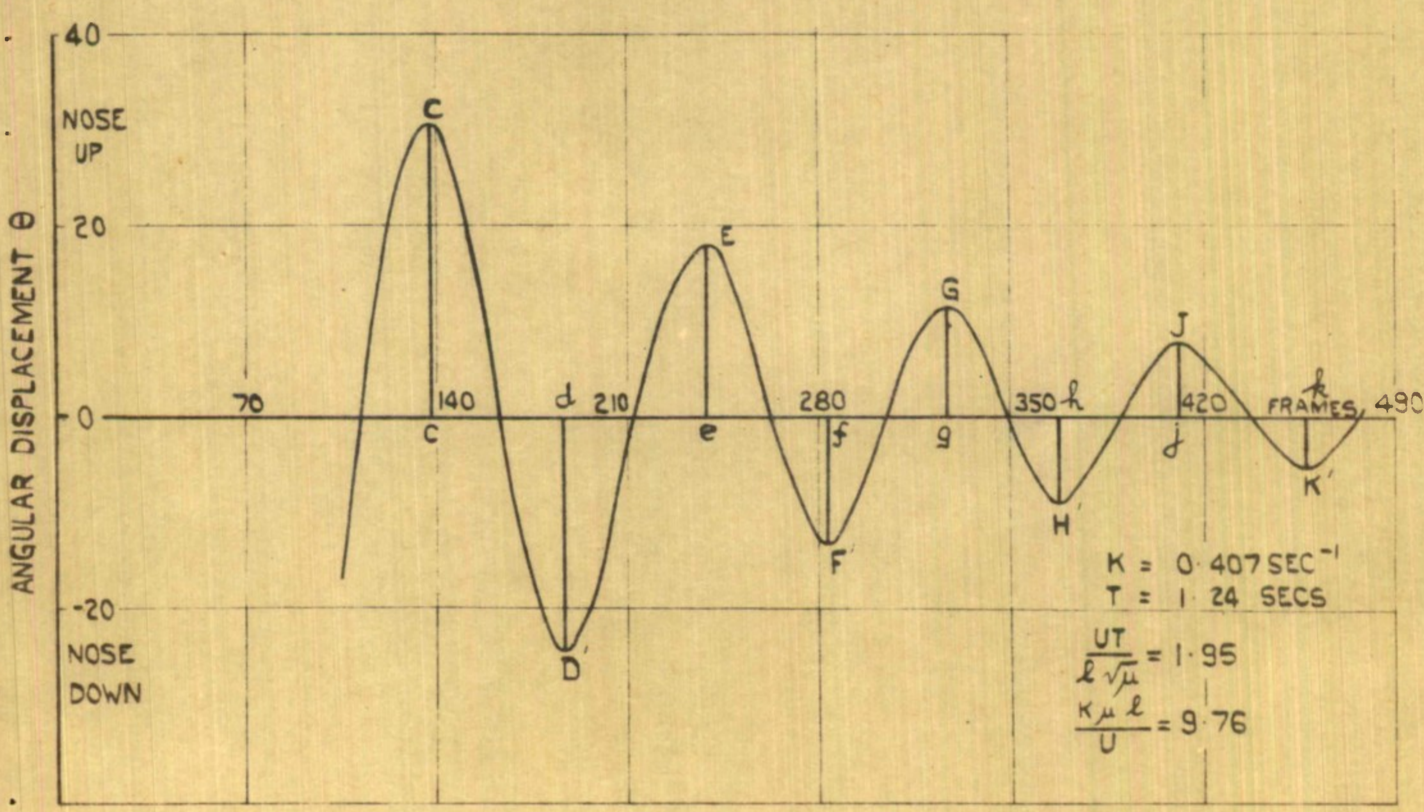
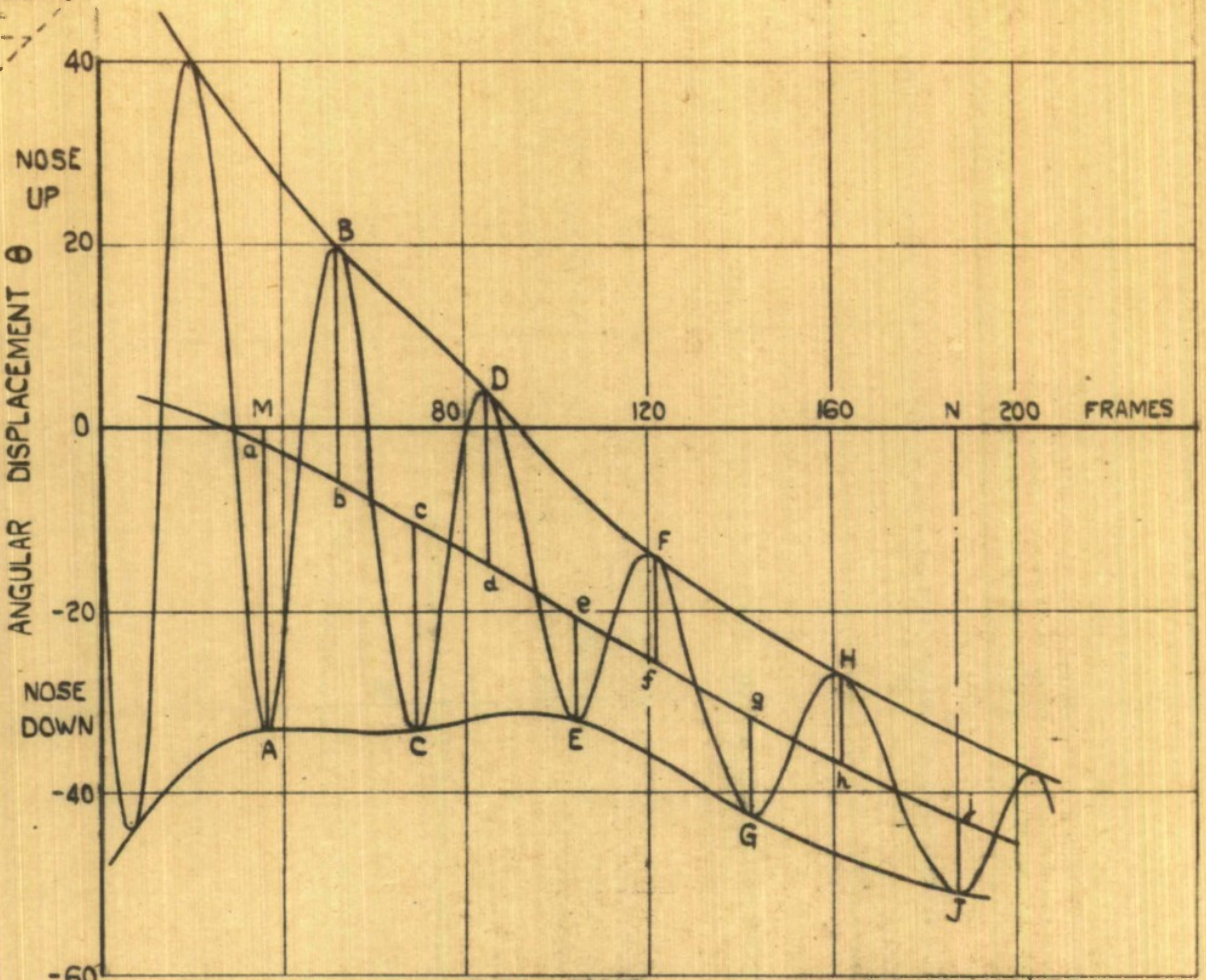


FIG. 5b. REPLOT OF CURVE IN FIG. 4.

FIG. 6.



FILM SPEED = 38·5 FRAMES/SEC.
RELEASE SPEED, U = 183 M.P.H.
LENGTH OF STORE, ℓ = 28·25 INS.
μ = 1402.

θ_1 ----- θ_8, θ_1	31·4	25·8	22·6	18·6	11·4	11·0	11·0	9·6	31·4
θ_2 ----- θ_9, θ_9	25·8	22·6	18·6	11·4	11·0	11·0	9·6	8·4	8·4
θ_1/θ_2	1·216	1·142	1·215	1·631	1·036	1·000	1·146	1·143	3·735
LOG θ_1/θ_2	0·195	0·133	0·195	0·489	0·036	0·0	0·136	0·134	1·318
τ FRAMES	16	17	16	19	17	20	21	26	152
τ SECS.	0·415	0·441	0·415	0·493	0·441	0·519	0·545	0·675	3·945
K	0·470	0·302	0·468	0·993	0·082	0·0	0·250	0·198	0·334

MEAN K = 0·344 SEC^{-1}

$$T = \frac{152}{4 \times 38\cdot5} = 0\cdot987 \text{ SEC.}$$

$$\frac{UT}{\ell\sqrt{\mu}} = 3\cdot01$$

$$\frac{K\mu\ell}{U} = 4\cdot23$$

IRREGULAR CURVE – METHOD OF ANALYSIS.

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